Laser Sounding Instrument using Oxygen A-Band for Atmospheric Pressure Sensing

Mark A. Stephen
NASA – Goddard Space Flight Center
Code 554
Greenbelt, MD 20771
301-614-6737
mark.a.stephen@nasa.gov

Jianping Mao
RSIS
Code 610.2
Greenbelt, MD 20771
301-614-6079
jmao@pop600.gsfc.nasa.gov

James B. Abshire
NASA – Goddard Space Flight Center
Code 690
Greenbelt, MD 20771
301-614-6081
James.B.Abshire.1@gsfc.nasa.gov

S. Randy Kawa
NASA – Goddard Space Flight Center
Code 613.3
Greenbelt, MD 20771
301-614-6004
Stephan.R.Kawa@gsfc.nasa.gov

Xiaoli Sun
NASA – Goddard Space Flight Center
Code 694
Greenbelt, MD 20771
301-614-6737
Xiaoli.Sun@gsfc.nasa.gov

Michael A. Krainak
NASA – Goddard Space Flight Center
Code 554
Greenbelt, MD 20771
301-286-4881
mkrainak@pop500.gsfc.nasa.gov

Abstract—**We report on the progress of an Oxygen spectroscopy laser sounding instrument designed as a calibration channel for a carbon dioxide (CO_2) laser sounding instrument. We have developed a pulsed, frequency-doubled, fiber laser transmitter for use in an oxygen instrument. The instrument concept uses the pressure broadening of spectroscopic lines of the diatomic oxygen A-band to deduce atmospheric pressure.**

There are many uses for this measurement but we are developing it primarily to make a measurement of the dry mixing ratio of CO_2. The CO_2 measurement can be affected by changes in atmospheric properties such as humidity, temperature and pressure. To remove these error sources requires measuring a stable, well-mixed gas like Oxygen.

We will report on the basic theory behind the instrument, measurements made at a test site at Goddard, review the current state of the instrument technologies and the necessary steps to bring them to space readiness, and review the current state of the instrument development.

1. Introduction

This research is directed toward developing a remote sensing instrument capable of measuring atmospheric pressure. The primary focus for the authors is a calibration channel for a carbon dioxide (CO_2) sensor, however there are many other uses for such an instrument, including: weather prediction, atmospheric modeling and dynamic gravity field measurements.

The CO_2 measurement of scientific interest is the fraction of CO_2 compared to the dry atmosphere – the so-called dry mixing ratio (DMR) – usually expressed in percentage or parts per million (ppm) in the case of CO_2. Because diatomic oxygen (O_2) has a constant dry mixing ratio of 20.95%, it is an ideal reference for measuring the variability of a gas like CO_2.

If one just measured the total number of CO_2 molecules in a certain volume of atmosphere, the biggest error sources would be the variability of atmospheric pressure and water vapor. The atmosphere is denser at higher pressures so more CO_2 will be measured at higher pressures. Similarly, increased atmospheric water vapor concentration will change the absolute (but not relative) percentages of other molecules. Measuring the CO_2 dry-mixing ratio by dividing by the O_2 concentration excludes both of these effects. Unfortunately, direct measurement of the O_2 concentration is difficult. Therefore we measure the atmospheric pressure and the water vapor concentration separately and deduce the O_2 concentration. Adequate water vapor data is available from the Atmospheric Infra-red Sounder (AIRS)[1] so we focus on the atmospheric pressure measurement required.

We use spectroscopy of pressure-broadened lines of the diatomic oxygen A-band as the basis for the measurement. Others have used similar methods of both passive [1] and active [2-5] spectroscopy with success. The oxygen dry mixing ratio stays constant at 20.95% so it makes a good reference for a variable gas like CO_2. We are developing a measurement technique that capitalizes on the spectroscopy work of others but uses new laser and instrument architectures.

The laser developed is a frequency-doubled, DFB seeded erbium-doped fiber amplifier (EDFA). It is a tunable, narrow frequency, rugged, efficient, high peak power device capable of very high-resolution spectroscopy. The details will be considered in a later section.

The instrument uses laser pulses reflecting from a hard target and measures the average atmospheric pressure of the column of air through which the laser pulses travel. This is in contrast to differential absorption lidar (DIAL) instruments that rely on atmospheric backscatter for their return signals. An instrument using a hard target return requires several orders of magnitude less transmitted laser power than one relying on atmospheric backscatter. This technique does not resolve range like a lidar instrument, however for atmospheric pressure, whose vertical distribution is well approximated by the hydrostatic relationship [6], this is not a substantial loss.

The spectroscopy method we employ is very similar to previous instruments. We will measure the absorption in the trough between two strongly absorbing lines in the oxygen A-band near 760 nm. This instrument design and component technology is being considered to easily extend to both aircraft and satellite but our development to date has been ground-based.

First we will analyze the theory behind the measurement. We will discuss the spectroscopy and pressure-broadening effects. In section 3 we will discuss the instrument design and performance and compare to theory.

2. Theoretical Analysis

In order to measure the CO_2 dry mixing ratio to a part per million (ppm), knowledge of the atmospheric pressure to <3 mbar is required. Korb et al measured atmospheric pressure to 1.5 – 2.0 mbar accuracy [5] using DIAL in the oxygen A-band. We propose a similar instrument but employing a different laser technology.

Using oxygen for this measurement is beneficial for several reasons. First, oxygen is well-mixed, both temporally and spatially, in the atmosphere so the concentration is constant and known. The oxygen A-band absorption near 760 nm is free from other atmospheric absorptions that could confuse or corrupt the measurements. The previous work in this spectral region proves the feasibility and the strength of the absorptions are also convenient to work with over the path lengths required as discussed in more detail later.

The transmission through the atmosphere is given by Beer's law:

$$T(w) = \exp[-K(w) \cdot L] \tag{1}$$

Where L is the path length of the light and K, the resonant absorption is given by,

$$K(w) = n \cdot S_j \cdot f \tag{2}$$

where S_j is the line strength parameter, n is the number density of O_2, defined in Eq. (3), and f is a lineshape function defined in Eqs. (4-6).

$$n = q \cdot (1 - q^*) \cdot \frac{P}{R \cdot T} \tag{3}$$

In Eq (3), q is the dry mixing volume ratio of O_2, equal to 20.95%, q* is water vapor concentration by volume, P is atmospheric pressure, R is the universal gas constant and T is the temperature of the atmosphere.

In order to calculate the expected absorption, we use a Voigt line shape. This function is the convolution of Gaussian and Lorentzian line shapes and is used when both Doppler and pressure broadening are significant. Doppler (or temperature) broadening is Gaussian and Collision (or pressure) broadening is Lorentzian. The Voigt function is then defined by:

$$f_V(w) = \int_{-\infty}^{\infty} f_G(w - w_o) \cdot f_L(w - w_o - \tau) \cdot d\tau \tag{4}$$

where w_o is the wavenumber of the absorption peak, w is the wavenumber and f_G and f_L are the Guassian and Lorentzian functions, respectively, defined as follows:

$$f_G(w) = \sqrt{\frac{\ln(2)}{\pi}} \cdot \frac{1}{\gamma_G} \cdot \exp\left[-\ln(2) \cdot \frac{(w - w_o)^2}{\gamma_G^{\,2}}\right] \tag{5}$$

$$f_L(w) = \frac{1}{\pi} \cdot \left[\frac{(\gamma_L/2)}{(w - w_o)^2 + (\gamma_L/2)^2}\right] \tag{6}$$

Where γ_G is the half width at half maximum (HWHM) gaussian linewidth and γ_L is the HWHM Lorentzian linewidth. The gaussian linewidth is defined, from Boltzman statistics [7], to be

$$\gamma_G = \frac{w_o}{c} \sqrt{2 \cdot R \cdot \ln(2) \cdot \left[\frac{T}{M}\right]} \tag{7}$$

Where c is the speed of light and M is the molar mass of the oxygen molecule. While the Lorentzian linewidth is defined as

$$\gamma_L(\omega_o) = \gamma_{air} \cdot P \cdot \left(\frac{T_o}{T}\right)^{n_{air}} \tag{8}$$

Where γ_{air} is air-broadened HWHM at T_o = 296K and n_{air} is the coefficient of temperature dependence of the air-broadened half-width. The values used in these calculations for S_j, γ_{air}, n_{air} w_o are from the HiTRAN [8], a database of measured and calculated parameters for atmospheric absorption spectra.

In the case of multiple lines with overlapping absorptions, Eq. (1) becomes

$$T(w) = \exp\{-[K_1(w) + K_2(w) + ...K_n(w)] \cdot L\} \qquad (9)$$

Where K_1, K_2,…K_n are calculated individually from values listed in HiTRAN for each line of interest. (The theory for a calculation of two lines is illustrated in Figure 1 - inset.)

The technique we explore in this research uses the absorption between two strongly absorbing oxygen absorption lines. We use this measurement away from the peak absorption to isolate the pressure broadening in the absorption. Because there is appreciable Doppler and pressure broadening in the oxygen lines of interest, we must distinquish between them. The Doppler broadening has a Guassian shape whereas the pressure broadening has a Lorentzian shape. The Lorentz function goes to zero much slower away from the absorption peak than does the Gaussian function. The line wing is therefore dominated by the pressure effect. Measuring the absorption between two closely spaced lines increases the amount of absorption from a single line, and decreases sensitivity to frequency drift [2].

The Figure 1 inset, is an example of an absorption calculation showing the transmission as a function of wavelength for the two lines of interest in the oxygen A-Band and the trough between them.

A modified version of the LIDAR equation, which calculates the column average due to a hard target return rather than range resolved atmospheric backscatter, is shown below.

$$E_{Rx}(\lambda) = E_{Tx}(\lambda) \cdot T_{BS} \cdot T_c \cdot T_r(\lambda) \cdot R_{target} \cdot \eta_{Rx} \qquad (10)$$

$$E_{Mon}(\lambda) = E_{Tx}(\lambda) \cdot R_{BS} \cdot \eta_{Mon} \qquad (11)$$

In this equation, E_{Rx} is the energy received, E_{Mon} is the energy measured at the monitor receiver, E_{Tx} is the energy from the transmitter, T_{BS} is the transmission of a beam splitter used to monitor the outgoing energy, R_{BS} is the reflectivity of this beam splitter, T_c is the transmission through the atmosphere that includes all continuum and scattering losses, T_r is the resonant transmission, η_{Rx} is the efficiency of the main instrument receiver, while η_{Mon} is the efficiency of the monitor receiver. (The term, η_{Rx}, used to represent the efficiency of the receiver, includes many terms that are often written out explicitly like the area of the receiver telescope and the inverse square dependence on range. These terms have been consolidated into the receiver efficiency because they would unnecessarily complicate the discussion.)

It is easily shown using Eqs. (10 & 11) that, if a reference wavelength is chosen such that $T_r(\lambda_{ref})$ equals one – meaning no resonant absorption at that wavelength – then the resonant transmission can be measured as follows:

$$T_r(\lambda) = \frac{E_{Rx}(\lambda) / E_{Mon}(\lambda)}{E_{Rx}(\lambda_{ref}) / E_{Mon}(\lambda_{ref})} \qquad (12)$$

This assumes that the only terms affected by a change in wavelength over the small tuning range (of ~200 pm) are those with the dependence written explicitly. The degree to which this is true will largely determine the accuracy and effectiveness of the instrument.

The pressure dependence of the absorption trough is calculated from Eq. (9) using the two dominant lines and illustrated in Figure 1. The slope of 0.73 % per mbar change in atmosphere is calculated from the result. In order to measure the CO_2 dry-mixing ratio to ~1ppm, requires knowledge of the atmospheric pressure to an accuracy of better than 3 mbar. This leads to a measurement accuracy of the resonant transmission to ~0.2%. Although very challenging, analysis and measurements mentioned earlier demonstrate it is feasible. Further analysis of the error sources of this type of measurement is available [9]. An instrument capable of an atmospheric pressure measurement to this accuracy would find many applications in addition to CO_2 calibration.

This trough between these two particular lines was chosen for several reasons. First, the line strengths of lines is temperature insensitive. This means that changes in temperature will have only small effects on the transmission spectrum. Also, the lines are strongly absorbing so the line wing still has a very appreciable absorption. Calculation of the absorption trough for a round trip path from a nadir-viewing satellite has around 50% transmission which is optimum. In addition, this wavelength overlaps nicely our laser technology – a frequency doubled EDFA. This is in contrast to Korb et al [5] who used the R branch rather than the P branch of the oxygen A-band.

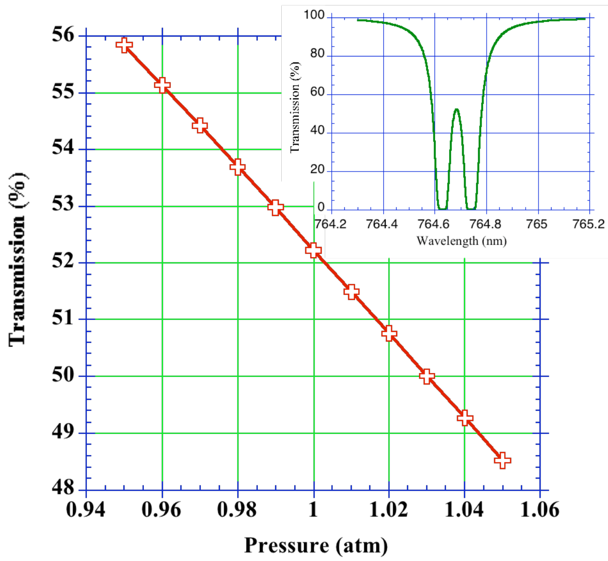

Figure 1 – Calculation of pressure dependence of the transmission through a 7 km horizontal path of atmosphere (round trip) at 764.7 nm (the trough between two strongly absorbing (and saturated) oxygen lines.) The inset shows the calculated transmission vs. wavelength at 1 atm.

3. INSTRUMENT

For the space measurement, we have base-lined a two spectral line instrument that measures only at a signal and a reference wavelength. However for the development of the instrument, tuning through the entire line is preferable in order to measure and assess noise sources and instrument uncertainties. The measurement technique is based on the fact that the only variation in wavelength response is from the absorption. However, if there are other instrument elements like etalon effects, errors will be introduced. Mathematically this can be seen if any of the terms in Eqs. (10, 11) have a wavelength dependence that is not explicitly written. If this is the case, then the division in Eq. (12) will not correctly cancel these terms and unknown errors will persist. Scanning across the whole line will allow us to track these changes and reduce or eliminate them. This effect is a common one in high fidelity spectroscopy instruments [10, 11].

In the present instrument set-up, the pulses from the laser transmitter are directed at a cooperative target via a transmitter telescope which is co-aligned with a receiver telescope. The light travels across an open section of atmosphere, rebounds from the target and is then collected by the receiver. The measurement we have performed is across a 443 meter round trip horizontal open path. The instrument layout is illustrated in Figure 2.

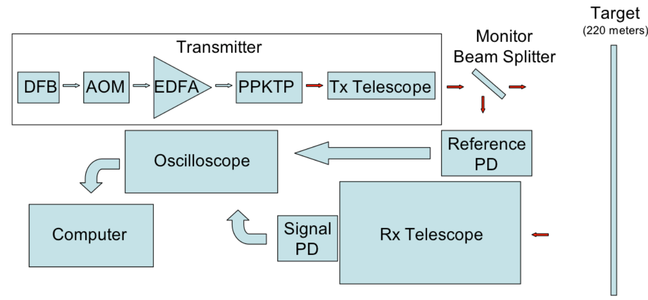

Figure 2 – Diagram of instrument set-up illustrating laser transmitter architecture, receiver telescope and laser propagation.

The laser transmitter is a DFB seeded, frequency doubled, EDFA. The basic architecture is shown in the transmitter box of Figure 2. The seed is a very narrow frequency (~1 MHz), wavelength tunable, DFB laser with a wavelength centered around 1530 nm. The wavelength is tuned by changing the drive current applied to the seed laser. The output of the seed is then externally modulated with a fiber-coupled acousto-optic modulator to yield transform limited, 200 ns laser pulses with 40 dB extinction ratio. These laser pulses are then coupled into an EDFA. The EDFA ouput is free-space coupled into a periodically-poled, KTP crystal to frequency double the fundamental to the 765 nm wavelength regime. We have reported on other versions of this transmitter operating at slightly different wavelengths in more detail. [12, 13]

It is the development and application of this laser technology where we are making the largest contribution from previous measurements. The previous pressure measurements referenced above, used dye and alexandrite lasers, which are far less efficient, had more frequency instability, and were much more difficult to use and to ruggedize for airplane or satellite platforms. This transmitter is fiber-based and capitalizes on substantial device development and engineering from the telecommunications industry. The components are high performance and cost effective. Because most of the system is fiber coupled, alignment is inherently stable and the system is lightweight and efficient. The spectrum is very narrow and stable.

For Frequency doubling the output of the EDFA, we use a 30 mm long PPKTP crystal. Its full width at half Maximum wavelength bandwidth is 760 pm so tuning at or above 90% of peak conversion is achieved over a tuning range of 260 pm. At high peak optical pump power, this will get even broader because of the saturation. After the doubling crystal, a long-wave pass filter separates the doubled frequency from the fundamental. The doubled light is then fiber coupled into the transmitter telescope.

Part of the transmitted signal beam is picked off with a beam splitter and sent to a photo-detector to monitor the output. This signal is used to track the energy of each pulse sent out by the system. We use an integrating sphere to reduce signal variation due to spatial variations in the laser beam. The detector output is AC-coupled to an oscilloscope.

We use a ten-inch Schmidt-Cassegrain telescope to collect the return signal. With custom mounts connected to the back end of the telescope, we used a fast lens to couple light into a fiber. This changes the telescope system from an f/10 to about an f/1.5 optical system. We are trying to optimize light collection so we used a large core (600 µm) fiber with a numerical aperture of 0.37. The fiber was then terminated in a large area PIN detector. The detector output was AC-coupled to an oscilloscope. The AC coupling allowed us to reduce the effect of the solar background that was larger than the signal.

The data was averaged on the oscilloscope and the magnitude (peak-to-valley) of the signal pulse was divided by the magnitude of the monitor pulse. Taking the ratio of the signal and the monitor eliminates the energy fluctuations from the transmission measurement as shown mathematically in Egs. (10-12). We then tuned the current of the DFB seed laser to tune the transmitter to a new wavelength and take another data point. In this way we measured the transmission of Figure 3, illustrated below.

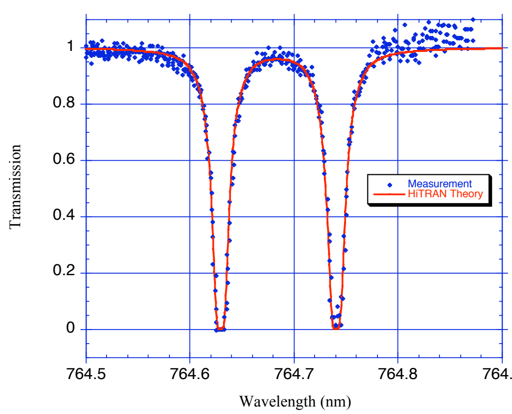

Figure 3 – Theory compared to measurement for the transmission through a 443-meter path. The scan was performed by changing the drive current of the DFB diode seed laser.

Using equation (9), the parameters from HiTRAN and measured values of pressure, temperature and humidity from a coincident weather station, the theoretical transmission curve was calculated. (For a satellite version of the instrument, the temperature and water vapor concentration are available from other satellite measurements like Atmospheric Infrared Sounder [14].) The calculation is compared to the actual measurement of our bread board instrument with excellent agreement between them.

4. Conclusions

To date, all the basic principles necessary for this instrument have been demonstrated. Analysis and previous measurements demonstrate the instrument measurement accuracy is achievable. Progress on the laser transmitter demonstrates all the fundamental performance elements can be realized. A preliminary instrument configuration has demonstrated the basic function of the system that has been used to measure the transmission through the atmosphere that shows the expected resonant absorption in the oxygen A-band.

There are several aspects of the measurement that still need to be optimized in order to realize the full potential of the instrument. The peak power of the transmitted signal was only about 50 mW due to peak power limitations in the present amplifier. We are currently improving the connector for this amplifier to allow higher peak powers but the power scaling above 100 watts has already been demonstrated in previous work [13]. For this measurement, the EDFA did not employ polarization maintaining fiber which helps minimize the frequency doubled energy. This is easily fixed and has been demonstrated in a different amplifier [12].

Because much of the effort has gone toward developing the laser transmitter, there are still many improvements to be made on the rest of the instrument. The oscilloscope used in this measurement can be replaced with a high speed Digital Acquistion Board and the data collection and processing can be greatly improved. This will lead to the ability to increase the speed of the scan which will help reduce noise sources do to atmospheric turbulence. The detectors are not optimized and will be replaced eventually with photon counters. An in-line solar filter will also greatly improve the signal-to-noise (SNR) ratio for the measurement. Longer path lengths will also increase the absorption in the trough and further increase the SNR at the wavelength of interest. Once the data collection has been improved, a more systematic analysis of the proper processing and averaging techniques can be explored.

We expect to continue to improve the instrument performance and make atmospheric pressure measurements and compare them to a coincident weather station to evaluate its accuracy.

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